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NEOGENE KARST SINKHOLE AND ITS DEPOSITS FROM GÓRAŻDŻE QUARRY, UPPER SILESIA – ARCHIVE FOR PALAEOENVIRONMENTAL RECONSTRUCTIONS

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Abstract: A sinkhole, developed in Middle Triassic limestones and filled with clastic and organic deposits, including lignite, was studied, in terms of its origin and age. The sinkhole represents a solution sinkhole, which originated through the subsidence of surficial deposits into an underlying cave system. The study permitted the recognition of three main stages of sinkhole evolution. During the initial stage, subterranean and surface karstification proceeded concurrently. As a result, a terra rossa cover developed at the surface and a cavern system was formed in the underlying bedrocks. During the second phase, both systems became connected and the soil cover subsided. This, in turn, involved the formation of a depression at the land surface and ponding of the drainage water. The pond was filled with plant debris, later giving rise to lignite formation. During the third and final stage, the sinkhole was filled with quartz sands with kaolinite, derived from eroded, Upper Cretaceous sandstones and marls.

Results of pollen analysis from the sinkhole indicate the presence of mesophytic forests and show a significant role of riparian forests and herbaceous vegetation. The occurrence of abundant, freshwater algae and the pollen of aquatic plants evidences sedimentation of the infill in a water body (pond). The apparent dominance of arcto-tertiary and cosmopolitan, palaeofloristical elements, as well as the occurrence of only sparse, palaeotropical elements (mainly subtropical), indicate a warm-temperate climate (cooler than during the Early and Middle Miocene period). A comparison of the sporomorph association from the sinkhole with those from other Neogene sites provides evidence of its Late Miocene age (Late Pannonian–Early Pontian).

Key words: palaeokarst, sinkhole deposits, palynology, Late Miocene, Upper Silesia.

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INTRODUCTION

The Upper Silesian-Cracow Upland abounds in palaeokarstic forms, filled with a variety of internal sediments. The palaeokarst phenomena include both covered and uncovered karst forms, filled with flowstones and clastic and organic deposits (Głazek, 1989; Szulc, 1998, 2012).

Most common palaeokarstic forms are sinkholes (dolines), reaching 30 m in depth and up to 300 m in diameter. Field studies led to the recognition of various kinds of the sinkhole. Two main types of sinkhole occur: dissolution sinkholes, open depressions at the bedrock surface, resulting from chemical erosion of limestone (open sinkholes, *exokarst*); and subsidence sinkholes, formed by movement of the cover materials into subsurface cave systems (*endokarst*). Both types differ also in composition and the sedimentary fabrics of their fills. As a rule, the open sinkholes are filled with undisturbed, well bedded clays, sands and a thicker complex of lignite. In contrast, the sedimentary fill of the subsidence sinkholes displays common deformations of the primary, sedimentary structures, including the original lamination. Brown coal forms thinner, discontinuous intercalations in the clastic deposits (Worobiec and Szulc, 2012).

It is remarkable that different types of sinkholes and their fillings may occur next to each other, at a distance of several hundred metres. This, in turn, raises the question of genetic controls and the time succession (stratigraphy) of the different palaeokarst systems.

The present study is focussed on a subsidence sinkhole in the Górażdże Quarry (Figs 1, 3A). In order to reconstruct the origin and age of the sinkhole, the authors examined in detail its sedimentary fill, the diagenetic fabrics of the fill and the parent rocks and the sporomorph composition of the

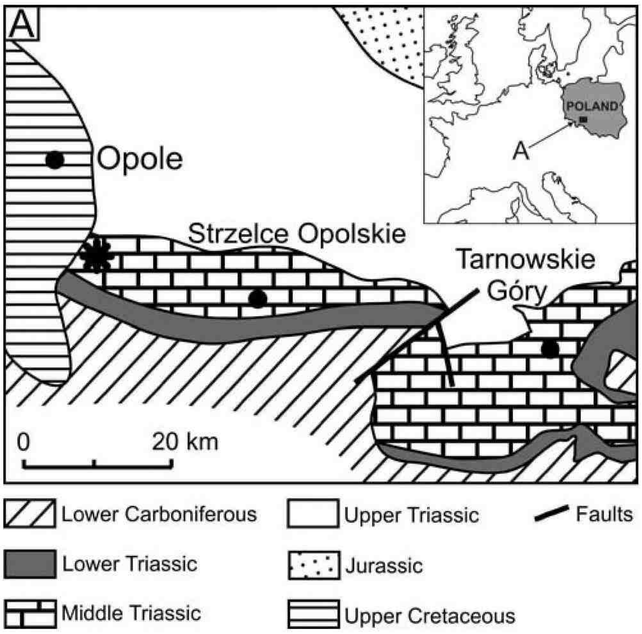


Fig. 1. Location map of Górażdże Quarry (asterisk) and general, geological map of region

sinkhole filling. One of the previous studies dealt with an open sinkhole in this region (Worobiec and Szulc, 2010a, b), so the new data may be viewed in the context of the previous study.

GEOLOGICAL SETTING

Palaeokarst forms, occurring in the western part of Upper Silesia, are developed mostly within two intervals of the Middle Triassic Muschelkalk carbonates, namely in the Górażdże Beds and in the Karchowice–Diplopora Beds (Fig. 2). Such a distribution is clearly controlled by the lithological properties of the rocks involved. Both of the complexes mentioned are composed of pure limestones, underlain by less permeable, marly deposits. Such a layer-cake arrangement implies the localization of karst processes, confined to the two intervals noted above.

The sinkhole under consideration developed in thick-bedded and coarse-grained, bioclastic, oncolithic and oolitic limestones, interbedded with fine-grained, nodular limestones, making up a succession, 15 m thick, in the Górażdże Beds. Pure limestones of the Górażdże Beds are underlain by marly sediments of the Upper Gogolin Beds. The marls form a poorly permeable horizon, which restricted the circulation of descending groundwater and thus limited the downward progress of the karstic processes.

The karstic processes were enhanced by relatively intense faulting of the Muschelkalk rocks during the late Triassic and Tertiary tectonic movements in the region (Assmann, 1944).

The palaeosinkholes and their fills are postdated by Quaternary tills and fluvioglacial sands.

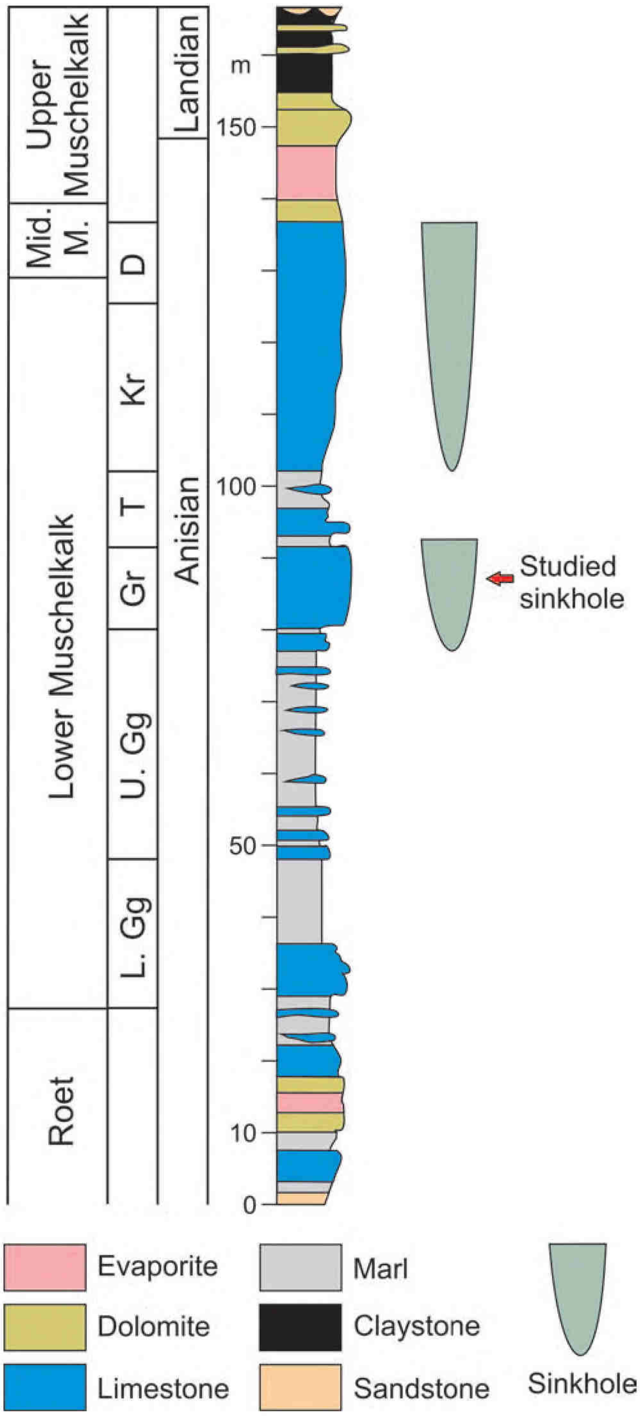


Fig. 2. Lithostratigraphical log of Middle Triassic from Upper Silesia. Abbreviations for lithostratigraphic units: L. Gg – Lower Gogolin Beds; U. Gg – Upper Gogolin Beds; Gr. – Górażdże Beds; T – Terebratula Beds; Kr – Karchowice Beds; D – Diplopora Beds

PREVIOUS STUDIES

Palaeokarst from Upper Silesia has not received any advanced and comprehensive study. The only paper on meteoric weathering of the basement carbonates, by Dżułyński and Kubicz (1971) concerned the diagenetic disintegration ("sandyfication") of the Muschelkalk limestones. In addition, some short reports and comments have been published in the booklet of the 32nd Speleological Symposium, organized in 1998 by Speleological Section of the Polish Copernicus Society of Naturalists (e.g., Koszara and Szynkiewicz, 1998). Some older publications, dealing with karst of the eastern part of Upper Silesia, did not include any definite results, concerning the age and origin of the palaeokarst systems of the region (Assmann, 1943; Hornig, 1956; Gers, 1963; Gilewska, 1964; Górzyński, 1964). According to better recognized examples from the Cracow Upland, Sudetes Mts. and Holy Cross Mts. (Gradziński, 1962, 1977; Głazek, 1989), it may be presumed that they formed both in Paleogene and Neogene times.

The previous, palaeobotanical examinations of the organic fraction, filling the karstic depressions in Silesia, gave very approximate, stratigraphic information, defining them as Neogene (Rogala and Sadowska, 2003) or generally as Tertiary in age (Baranowska-Zarzycka, 1980; Wojtanowska and Szynkiewicz, 1998).

The most recent studies on the paleokarst, concerning mainly the age of the karst filling, have been made for only one open sinkhole, occurring some 7 km SW from the Górażdże site, at Tarnów Opolski (Worobiec and Szulc, 2010a, b; Worobiec, 2011). The results permitted determination of the age of the lignite-filled sinkhole as Middle Miocene and reconstruction of the genesis of one type of open sinkhole.

The presence of some Neogene sites in SW Poland that were previously examined with respect to palynology permits the comparison of the sporomorph association studied with other pollen assemblages, as well as an age determination for the sinkhole infill. Some of the deposits originated from water bodies (e.g., Józefina – Worobiec *et al.*, 2009; Worobiec and Gedl, 2010). However, with the exception of the sinkhole at Tarnów Opolski (Worobiec and Szulc, 2010a, b; Worobiec, 2011), no detailed, palynological research has been conducted on the palaeosinkholes.

MATERIALS AND METHODS

A detailed study was carried out on the largest sinkhole, developed in the NW part of the quarry (Fig. 3A, GPS coordinates – N: 50°32'3.58"; E: 18°2'23.29"). The fill of this sinkhole was the subject of careful field examination, concerning its stratigraphy, depositional and deformational structures, mineralogical composition, diagenetic features (Figs 3–5), palynological and palaeoenvironmental context, and age determination. Since a significant part of the sinkhole fill was covered by scree material, extensive excavation work was necessary before the sedimentological and stratigraphical studies. After the fieldwork, 36 samples of the sinkhole deposits were taken for laboratory work, including thin-section analysis, SEM examination and X-ray diffraction. This laboratory work led to recognition of the dominant mineralogies of the fill, its early and late diagenetic changes and their palaeoenvironmental controls.

The parent rocks were examined by means of optical and scanning microscopy, in order to recognise the diagenesis, accompanying the sinkhole formation and infill deposition.

Palynology

The material for pollen analysis was collected from the sinkhole (Fig. 6) in May, 2009. In addition, in the years 2010–2012, samples were collected from the deposits, lying above the palaeokarst. A total of 15 samples of the sediment, filling the sinkhole (numbered 1–7), and more than 20 samples from the covering deposits (named GL) were taken (Fig. 4I). Samples no.: 1, 2a, 2b, 3a–3d, 4a–4c, 5a, 5b, and 6 were taken from the dark coaly sediment, visible in the walls of the sinkhole. Samples no. 7a and 7b were taken from the yellow sediment in the middle part of the sinkhole (Fig. 6). The samples were processed in the Laboratory of the W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków, according to the modified Erdtman's acetolysis method (Faegri and Iversen, 1975; Moore *et al.*, 1991), using hydrofluoric acid to remove mineral matter. Additionally, the material was sieved at 5 μm on a nylon mesh. Microscope slides were made, using glycerine jelly or glycerine as a mounting medium. Four microscope slides from each sample were studied. The rock samples, palynolgical residues and slides are stored in the W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków.

Data from the spore-pollen spectra were used to construct a simplified diagram, presenting the frequencies of sporomorphs (pollen grains and spores), characteristic for various plant communities, and algae (Fig. 7A). The percentage shares of the sporomorph groups, presented in the diagram, were calculated from the total sum of pollen grains and spores; the proportion of algal micro-remains was computed separately in relation to the total sum, using the POLPAL computer program (Nalepka and Walanus, 2003).

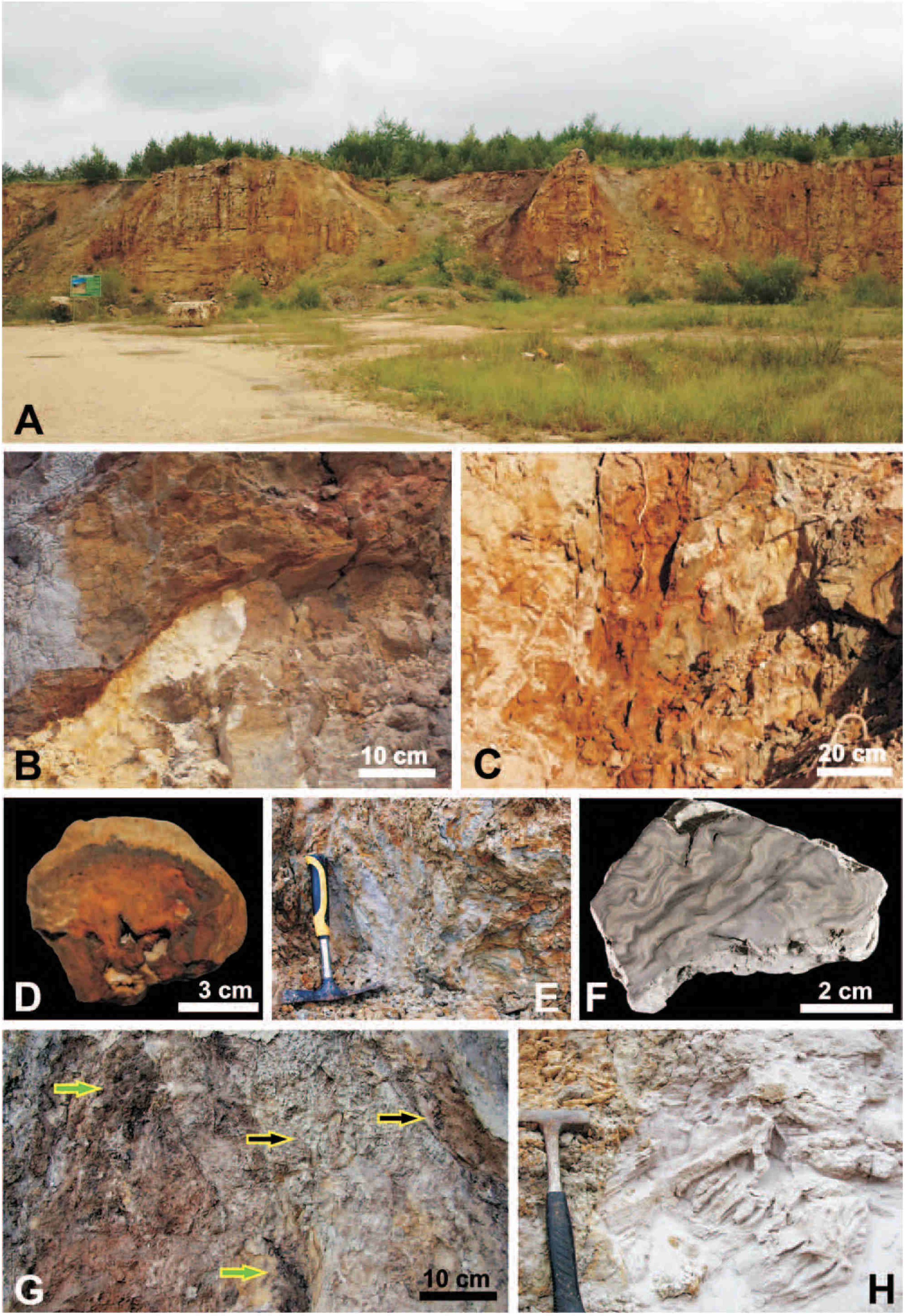
The identified sporomorph taxa were classified to an appropriate palaeofloristical element, mainly on the basis of the Atlas of Pollen and Spores of the Polish Neogene (Stuchlik *et al.*, 2001, 2002, 2009), and the checklist of selected pollen and spore taxa from the Neogene deposits, proposed by Ziembińska-Tworzydło *et al.* (1994). In the material studied, the following palaeofloristical elements were distinguished: palaeotropical (P), including: tropical (P1) and subtropical (P2), and arctotertiary (A), including: warm-temperate (A1) and temperate (A2), as well as cosmopolitan (P/A). The proportions of sporomorphs of the particular palaeofloristical elements are presented in Figure 7B.

Microphotographs of selected sporomorphs and non-pollen palynomorphs (Figs 8, 9) were taken, using a NIKON Eclipse microscope, fitted with a Canon digital camera.

DESCRIPTION OF SINKHOLE AND ITS FILLING

The authors studied an assemblage of three large sinkholes, developed within pure limestone rocks of the Górażdże Beds (Fig. 3A). Secondary, remnant crests divide the sinkhole into smaller furrows. It is worth noting that the sinkholes are grouped around a concentration of faults and fractures, affecting the NW part of the quarry.

For detailed examination the authors chose the largest, sinkhole with an hour-glass shape, reaching 17 m across


A
B
10 cm
C
20 cm
D
3 cm
E
F
2 cm
G
10 cm
H

and more than 12 m deep. The total depth is unknown owing to a scree that covers the lowest part of the outcrop.

The sinkhole fill shows a characteristic succession (Figs 3, 5); the topmost part of the host limestones (headrock) is disintegrated and built of weakly cemented, minute calcite crystals, which fell into a powder on hammering (Figs 3B; 4A, B, H). The weathered debris of limestones, which may reach up to 1 m in thickness, is covered with a firm, brownish crust, composed of clays and iron hydroxides that impregnate the floor materials of the sinkhole (Fig. 3B). Since this impregnation lines the margins of the sinkhole, it could be recognized as intrinsic part of the parent rock, buffering the unaltered limestones from the sedimentary fill. Merino and Banerjee (2008) called this zone the metasomatic front.

The ferric impregnation is covered by terra rossa-type variegated clays (mostly illite and kaolinite) and muds, interlayered with thin streaks of sands, 1.5 m-thick (Fig. 3C). Limonitic concretions and coated grains, forming aggregates up to 0.5 m in size (Fig. 3D), are a common component of this package. Some diagnostic fabrics (glaebules and rhizoliths) are ubiquitous in this part of fill and typical for pedogenic processes.

The next part of the fill is a complex of grey clays and lignite deposits (Figs 3E, F). The youngest complex of the sinkhole fill is 4 metres of light-coloured quartz sands with kaolinite, known in the iron industry as "moulding sands" (Fig. 3B). In the lignite deposits, large (up to 40 cm in size) chert pebbles occur, leached from the Triassic parent rocks (Fig. 4F). The cherts display common striping and blackening, which resulted from the introduction of a very fine organic dark pigment and pyrite into the micropores (Fig. 4G). It is noteworthy that the cherts come from the Karchowice Beds, which means from limestones, lying at least 20 metres above the present position of the cherts and absent in the Górażdże section (see Fig. 2). Another common, microscopic component of this complex is chalcedony cement, developed mostly within the lignite deposits (Fig. 4E).

The palaeokarst rugged surface is covered with fluvioglacial sands and clays, comprising organic-rich palaeosoils (Fig. 4H).

RESULTS OF PALYNOLOGICAL STUDIES

Samples from the sinkhole

Five samples, nos. 5a, 5b and 6, taken from dark sediment, as well as samples nos. 7a, and 7b, taken from yellow sediment in the middle part of the palaeosinkhole (Fig. 6), were barren or they yielded only sparse sporomorphs. Rich and very well preserved sporomorphs were found in six samples from (2a, 2b, 3a–3c, and 4c), collected from the dark coloured material. Pollen spectra from these samples are taxonomically diversified (Tab. 1). In four samples nos. 1, 3d, 4a, and 4b, the same taxa were found as in the best six samples, but frequencies of the sporomorphs were distinctly lower. Also the sporomorphs and algae were often corroded.

Among conifers, the pollen grains of *Pinus* (mainly *Pinus sylvestris* type) are the most frequent. Pollen of *Tsuga*, *Sciadopitys*, *Picea*, *Cathaya*, and *Taxodium/Glyptostrobus* regularly occurs. Deciduous trees are represented mainly by *Betula*, *Alnus*, *Salix*, *Quercus*, *Ulmus*, *Carpinus*, *Castanea/Castanopsis*, *Fagus*, *Pterocarya*, and *Carya*. Among shrubs, the pollen of Ericaceae and *Myrica* predominates. Herbs are very abundant (up to 40%); among them, Poaceae, Cyperaceae, Asteraceae, Polygonaceae, and Apiaceae regularly occur. Aquatic and near-water plants are represented by Sparganiaceae, *Potamogeton*, *Typha*, Nymphaeaceae, and Alismataceae. Among spores, Polypodiaceae *s.l.* (ferns) and *Sphagnum* are the most frequent. In some samples, other moss spores (Bryidae) are also very numerous.

Organic-walled, algal microfossils, including mainly *Sigmopollis*, *Botryococcus*, *Pediastrum*, and Zygnemataceae zygospores (e.g., related to the recent genera *Spirogyra*, *Mougeotia* and *Zygnema*), are relatively frequent. All identified, algal remains represent freshwater taxa. The frequency of the algal microfossils in particular samples varies from 12–32% (Fig. 7A). In addition, one sporocarp of the epiphyllous micro-fungi Microthyriales has been recorded. In all samples, fungal spores and plant tissues are very rare.

The composition of sporomorph associations from the samples studied shows an apparent dominance of arctotertiary (including warm-temperate and temperate) and cosmopolitan, palaeofloristical elements (Fig. 7B). Palaeotropical elements are represented mainly by subtropical and palaeotropical/warm-temperate taxa (e.g., spores of *Leiotriletes wolffi* and *Neogenisporis* sp., as well as pollen grains of *Cupuliferoipollenites oviformis*, *Ilexpollenites iliacus*, *Momipites* sp., *Quercoidites henrici*, *Reevesiapollis triangulus*, *Symplocoipollenites* sp., *Tricolporopollenites exactus*, *T. fallax*, *T. indeterminatus*, and *T. liblarensis*).

Samples from fluvioglacial deposits

Eighteen samples, taken from the deposits lying above the palaeokarst, were barren or yielded sparse sporomorphs. The most frequent and best preserved sporomorphs were found in 2 samples: GL 4B(1) and GL 12(2). All samples studied were strongly dominated by bisaccate pollen, mainly *Pinus* with an admixture of *Picea* and *Abies*. Among deciduous trees and shrubs, pollen grains of *Betula* and *Alnus* are the most frequent. Additionally, pollen of *Ulmus*, *Quercus*, *Corylus*, *Carpinus*, *Fraxinus*, *Salix*, *Tilia*, and others, is present. Herbs are represented mainly by Cyperaceae

Fig. 3. Sinkhole at Górażdże and its sedimentary fill. **A.** Sinkholes in quarry. Middle sinkhole studied in detail, **B.** Contact between disintegrated parent limestones and terra rossa fill (metasomatic zone), **C.** Terra rossa deposits. **D.** Limonite concretion from terra rossa deposits. **E.** Deformed grey clays. **F.** Slab of grey clays, showing plastic slump and creeping deformations. **G.** Synsedimentary faults (black arrows) affecting lignite-bearing (green arrows) grey clays. Photograph taken from marginal part of sinkhole fill. **H.** Cross-stratified moulding sands

Table 1

Results of palynological analysis (number of sporomorphs) of samples from sinkhole fill and covering Quaternary deposits

TAXON/SAMPLE	GL 4B (1)	GL 12 (2)	2a	2b	3a	3b	3c	4c
MOSSES								
Sphagnaceae: *Sphagnum*	3	1	19	13	15	17	30	3
HORNWORTS								
Anthocerotaceae								1
CLUB MOSSES								
Lycopodiaceae: *Lycopodium*	15	14			3			
FERNS								
?Gleicheniaceae (*Neogenisporis* sp.)						2		
Lygodiaceae (*Leiotriletes wolffi*)				1		2		1
Osmundaceae			1	1	1		2	
Polypodiaceae					1		1	
Polypodiaceae, Davalliaceae	19	2	24	18	18	35	21	9
CONIFERS								
Cupressaceae								
Sequoia/Sequoiadendron/ Metasequoia							1	
Taxodium/Glyptostrobus			6	3	4	6	20	1
Pinaceae								
Abies	4	3	3	2		3		1
Cathaya/Pinus haplohylon type	1		4	4	2	3	12	7
Cedrus				2				
Keteleeria			2			1		1
Picea	12	91	7	4	1	4	2	22
Pinus sylvestris type	153	97	45	92	44	66	34	176
Tsuga			8	15	1	14	11	19
Sciadopityaceae: *Sciadopitys*			4	2	6	9	12	4
DECIDUOUS TREES AND SHRUBS								
Adoxaceae				1		1		
Altingiaceae: *Liquidambar*			2				3	
Aquifoliaceae: *Ilex*			1		1	1	1	
?Arecaceae, ?Butomaceae							2	
Betulaceae								
Alnus	21	214	25	9	20	14	22	6
Betula	58	80	5	1	72	13	11	1
Carpinus	3	7	1	4	1	7	4	1
Corylus	5	6	4	1				1
Clethraceae, Cyrillaceae					1		1	
Cornaceae: *Nyssa*				1			3	1
Ericaceae	1		19	26	17	28	33	5
Eucommiaceae: *Eucommia*					1		1	
Fabaceae								
(*Tricolporopollenites fallax*)					1		3	1
(*Tricolporopollenites liblarensis*)			1				2	
Fagaceae								
Castanea/Castanopsis/Lithocarpus			6		3	2	3	4
Fagus	3	3	2	2	3	5	3	1
Quercoideae (*Quercoidites henrici*)			3			2	1	
Quercus	9	7	12	8	12	10	4	10
Hamamelidaceae: *Parrotia/Distylium*				1				
Juglandaceae								
Carya			1	2	1	2	2	

TAXON/SAMPLE	GL 4B (1)	GL 12 (2)	2a	2b	3a	3b	3c	4c
Engelhardia/Alfaroa/Oreomunnea				1			2	
Juglans	1			3	1	1		
Pterocarya			5	3	2	1	1	2
Magnoliaceae: *Liriodendron*				1				
Malvaceae: Tilioideae	3	5		1		2		
Myricaceae: *Myrica*			3	3	3	3	3	
Oleaceae: *Fraxinus*	2	5	1		1		4	
Rhamnaceae					1			
Rosaceae	1	2			1		1	
Salicaceae: *Salix*	9	2	3		29	5	6	
Sapindaceae								
Acer						1		
Aesculus					2			
Santalaceae								
Arceuthobium			2				1	
Viscum		1						
Symplocaceae: *Symplocos*							1	
Ulmaceae								
Ulmus		14						
Ulmus/Zelkova			9	7	1	4	3	1
HERBS								
Alismataceae: *Sagittaria*						1		
Amaranthaceae, incl. Chenopodiaceae			1	1	1			
Apiaceae	2		5		1	2	4	1
Asteraceae								
Asteroideae	1	2		1	4	1		1
Cichorioideae	3			1	1	1		1
Caryophyllaceae				1			1	
Cyperaceae	18	12	10	9	3	18	3	3
Lamiaceae			2	1	3	2	1	
Nymphaeaceae								
Nuphar			8	8	1	8		14
Nymphaea				2	1	1	5	
Onagraceae			1	1				
Poaceae: Pooideae	8	6	59	75	66	88	55	47
Plantaginaceae: *Plantago*					2			
Polygonaceae: *Polygonum persicaria* type			2	2		6	1	2
Potamogetonaceae: *Potamogeton*		1		1		3	2	1
Ranunculaceae: *Thalictrum*						1		
Sparganiaceae, Typhaceae	2	8	34	14	33	26	36	10
Typhaceae: *Typha latifolia* type	1				1			
Urticaceae	3		1		3			
Other pollen and spores	4		11	5	11	1	22	6
Sum of sporomorphs	362	582	343	341	386	406	367	362

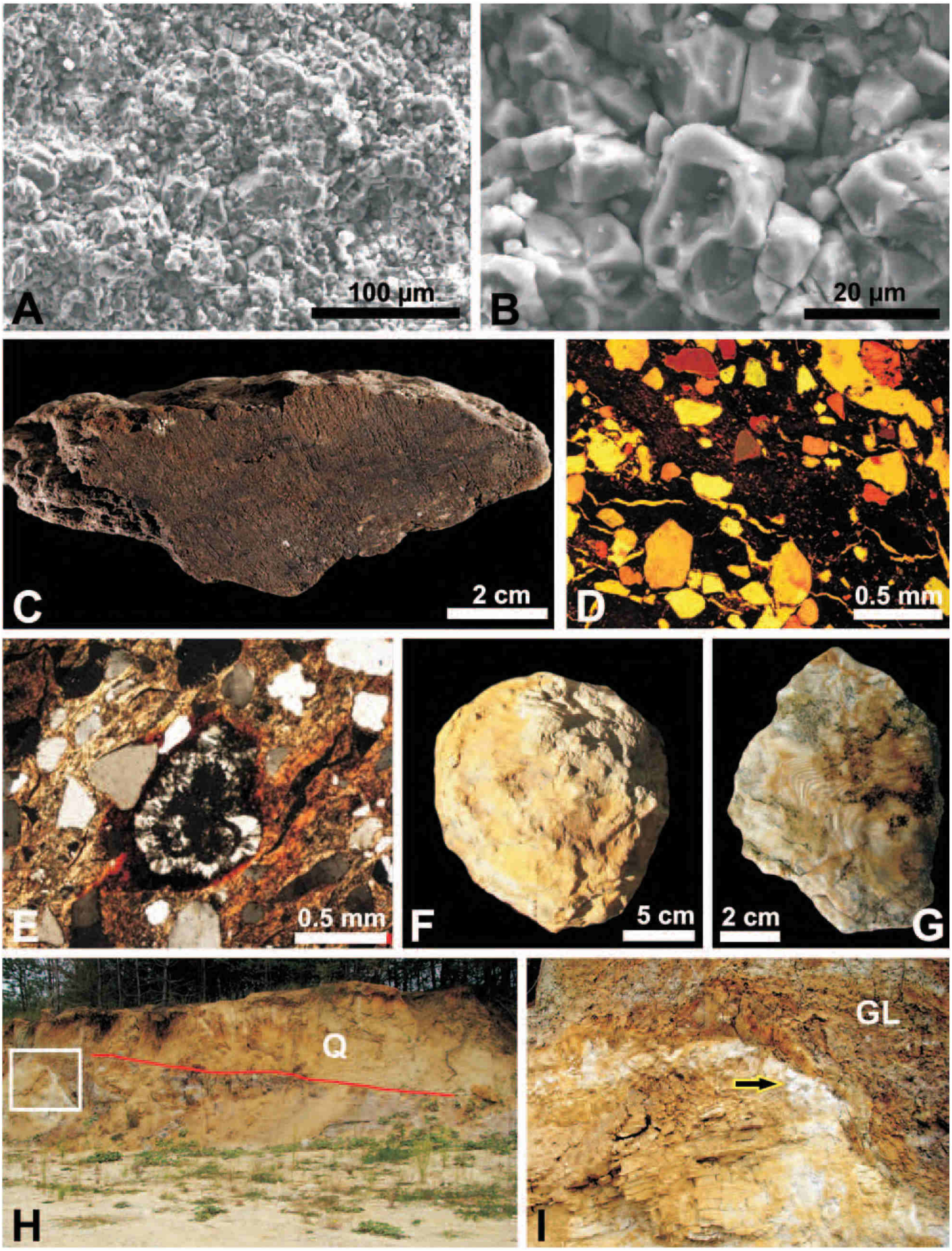


Fig. 4. Sinkhole at Górażdże and its sedimentary fill (other features). **A, B.** SEM photographs of disintegrated limestones from metasomatic zone. **C.** Close up view of lignite sediments comprising some detrital quartz grains. **D.** Thin-section photograph of lignite. Angular quartz grains are coated with organic matter. X nicols. **E.** Neomorphic chalcedony, precipitated in lignite deposits. **F, G.** Triassic cherts, enclosed in sinkhole fill. **H.** Topmost part of paleokarst surface, eroded and covered by Quaternary, fluvioglacial sands (Q). Insert – see Fig. 4 I. **I.** Small remnant knob of limestones (Terebratula Beds), disintegrated (arrow) and covered by variegated clays and silts. GL – location of samples, collected for palynological examination

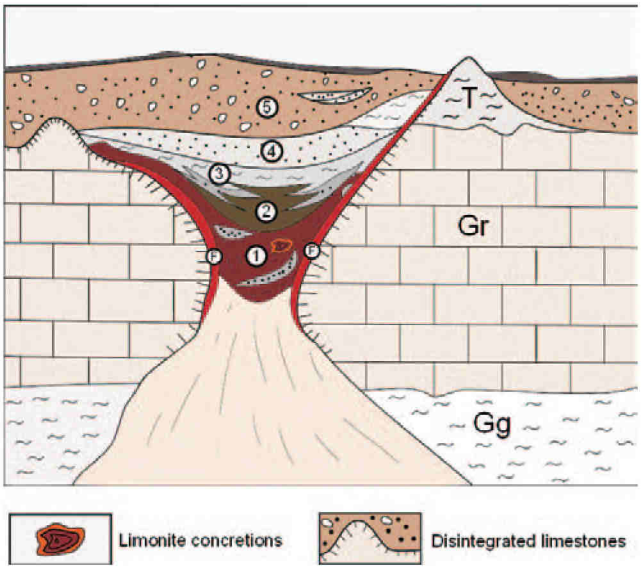


Fig. 5. Scheme diagram of sinkhole and its fill. For sake of clarity, final collapse deformations neglected. Gg – marls of Upper Gogolin Beds; Gr – bioclastic limestones of Górażdże Beds; T – marls of Terebratula Beds. 1. Terra rossa pedogenic deposits, 2. lignite, 3. Grey clays and silts, 4. Moulding sands and clays, 5. Quaternary till and sands, F. Metasomatic zone fabrics

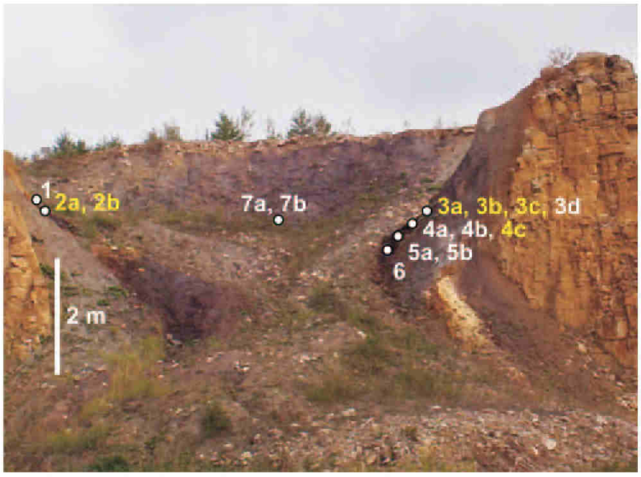


Fig. 6. Sampling points for palynological examination. Yellow – samples with rich and very well preserved sporomorphs, white samples barren or with only sparse sporomorphs

and Poaceae, as well as *Sparganium*, Asteraceae, Urticaceae and Apiaceae. Among spores, Polypodiaceae *s.l.* and *Lycopodium* are most frequent. No palaeotropical (or even "Tertiary") taxa have been recorded (Fig 7B). Algae are represented mainly by *Sigmopollis*, Zygnemataceae zygospores (e.g., related to the Recent genera *Spirogyra*, *Zygnema* and *Mougeotia*), *Botryococcus*, and *Pediastrum* (different species than *Pediastrum* present in the sinkhole). The frequency of algal microfossils is about 15–20% (Fig. 7A). In these samples, no epiphyllous micro-fungi were encountered, but some animal remains (e.g., probably oocytes of Neorhabdocoela flatworms) were found.

DISCUSSION OF PALYNOLOGICAL RESULTS

Palynoflora from sinkhole fill – palaeoenvironmental data

The results of pollen analysis from the sinkhole indicate the presence of mixed, mesophytic forests and show a significant role of herbaceous and riparian vegetation (Fig. 7A). The occurrence of abundant freshwater algae and pollen of aquatic plants indicates the presence of a water body (pond). Green algae (Chlorophyta), such as Zygnemataceae, *Botryococcus* and *Pediastrum*, as well as *Sigmopollis*, were major components of the algal community. Most of the algae identified prefer mesotrophic to eutrophic conditions and are characteristic of stagnant or slowly flowing, shallow water (Kadłubowska, 1972; Pals *et al.*, 1980; van Geel *et al.*, 1983; van Geel and Grenfell, 1996; Worobiec and Worobiec, 2008; Worobiec, 2010, 2011). In the water body, *Nuphar*, *Nymphaea*, and *Potamogeton* grew, along with *Typha* and *Sparganium* in shallow water and in the marginal zone. The pond was surrounded by vegetation, composed of herbs (sedges, grasses, and others), and riparian forests, dominated by *Alnus*, *Salix*, *Ulmus*, *Pterocarya*, *Carya*, and *Betula*. Drier terrains presumably were covered by mixed forests, composed of: *Pinus*, *Tsuga*, *Picea*, *Quercus*, *Carpinus*, *Castanea*, *Fagus*, *Betula*, and others. In these forests, only a small admixture of thermophilous plants was present. Ericaceae were probably the main components of bush swamps that occurred in the vicinity or they were components of the ground cover of the forests. Sparse pollen grains of *Nyssa* and *Taxodium/Glyptostrobus*, encountered in the material studied, suggest that swamp forests were not significant plant communities at that time.

The predominance of trees of the genera, growing now under temperate and warm temperate climatic conditions, and accounting for a very low proportion of tropical plants, is well demonstrated (Fig. 7B). All these observations indicate that the climate during deposition of the sediments in the sinkhole was warm-temperate (cooler than during the Early and Middle Miocene period, but still warmer than the present-day climate of Poland), mild (without severe winters) and mid-wet.

Palynoflora from sinkhole fill – comparison with other Neogene sites

The differences between the Górażdże and the previously studied Tarnów Opolski sinkhole palynofloras (Fig. 10; Worobiec and Szulc, 2010a, b) are mainly quantitative. The composition of pollen assemblages of aquatic plants and herbs, surrounding the water body, is similar in both sinkholes. The differences are clearly visible in the composition of forest taxa. In Tarnów Opolski, swamp forests were important components of the vegetation (Worobiec and Szulc, 2010a, b), whereas in the palynoflora studied, taxa characteristic of mesophytic and riparian forests predominate. Also herbs and Ericaceae are distinctly more frequent, which is presumably connected with presence of open-landscape plant communities. In the Górażdże mate-

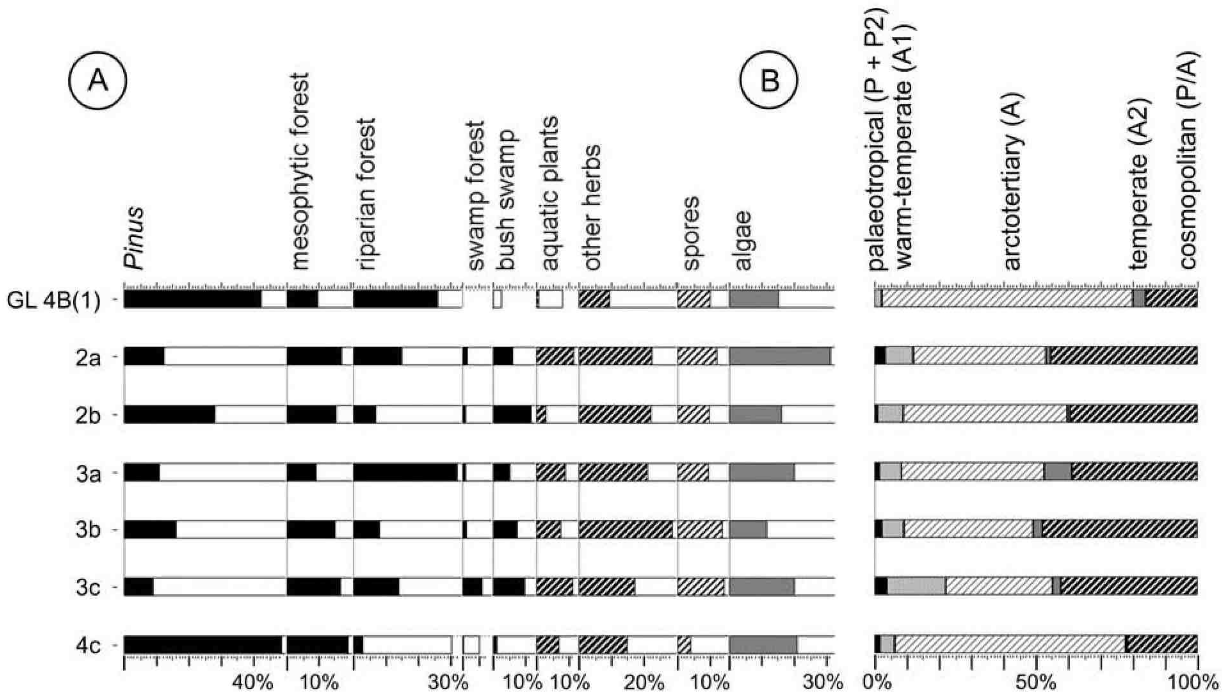


Fig. 7. **A.** Simplified diagram, presenting frequencies of pollen grains and spores, characteristic of various plant communities, and algae; **B.** diagram presenting proportions of sporomorphs of particular palaeofloristical elements

rial, sporomorphs, representing so-called "Tertiary" elements, are less common. Also the frequencies of palaeotropical taxa are lower. Such differences indicate that the material studied is younger than the Middle Miocene deposits at Tarnów Opolski.

The Górażdże palynoflora shows similarities to the Late Miocene palynoflora from Józefina (Fig. 10), Kraków-Silesia Upland (Worobiec *et al.*, 2009; Worobiec and Gedl, 2010), which also comes from sediment, deposited in a water body. In both palynofloras, the frequencies of palaeotropical taxa are similar (about a few per cent of the spore-pollen spectra). The Józefina palynoflora is dominated by *Pinus* (mainly *Pinus sylvestris* type) as well as *Tsuga*, *Sciadopitys*, *Abies*, *Picea* and *Cathaya*, while pollen grains of *Taxodium/Glyptostrobus* are very rare. The main difference between the Górażdże and Józefina palynofloras is the composition of deciduous trees. In the Józefina material, pollen of *Fagus*, *Carpinus*, *Pterocarya*, *Carya* and *Liquidambar* predominate. In addition, in the material studied, the pollen grains of herbs are distinctly more frequent.

The palynoflora studied is also similar to Late Miocene palynofloras from Sośnica, SW Poland (Stachurska *et al.*, 1973) and Gnojna (Fig. 10), SW Poland (Sadowska, 1991). In these palynofloras, sparse, palaeotropical elements occur. The main components of the Sośnica and Gnojna assemblages are trees, growing in mesophytic and riparian forests (e.g., *Pinus*, *Carpinus*, *Ulmus*, *Quercus*, *Alnus*, *Betula*, *Fagus*, *Liquidambar*, *Pterocarya*, and *Carya*). Pollen grains of *Taxodium/Glyptostrobus* and *Nyssa* are sparse. The Sośnica and Gnojna palynofloras are very similar to each other; the differences between them seem to have mainly a facies character. In the contrast to these two localities, the pollen of herbs is distinctly more frequent in the material studied. In each sample from the Górażdże sinkhole, the pollen grains of herbs exceed 20% of the spore-pollen spectrum, whereas in the Sośnica and Gnojna palynofloras, herbs are not numerous, amounting to a few per cent.

The Górażdże palynoflora is also slightly similar to the Late Miocene palynoflora from Gozdnica (profile 4), SW Poland (Fig. 10; Stachurska *et al.*, 1971), which is also dominated by arctotertiary elements. The main component of the Gozdnica palynoflora is *Pinus*. Among angiosperms, *Liquidambar*, *Fagus*, Clethraceae-Cyrillaceae, *Symplocos*, and *Ilex* pollen predominates. The pollen grains of palaeotropical taxa do not exceed 1–2% of pollen spectra. Herbs are represented mainly by grasses, but their grains are not numerous. The main difference between the Górażdże and Gozdnica palynofloras is the abundance of *Ilex*, *Symplocos*, and *Taxodium/Glyptostrobus* pollen grains in the latter.

On the other hand, the pollen assemblage studied differs from the Pliocene palynoflora from Kłodzko (Fig. 10), the Kłodzko Basin, Central Sudetes (Jahn *et al.*, 1984), which is dominated by conifers, with a high proportion of *Picea* pollen. The other difference is the abundance of *Aesculus* pollen in the Kłodzko II profile. The assemblage studied differs from the Pliocene palynoflora of the fluvial sediments at Tułowice (Fig. 10), SE Silesian Upland (Badura *et al.*, 2006), mainly in the presence of *Taxodium/Glyptostrobus*, *Quercoidites henrici*, *Tricolporopollenites liblarensis*, *T. fallax* and *Myrica*, a higher frequency of *Tsuga*, *Sciadopitys*, as well as the absence of *Theligonum* and *Hippophae* pollen in the latter.

The palynoflora from Górażdże is also richer in palaeotropical and warm-temperate taxa than the Pliocene palynofloras of Mizerna-Nowa, West Carpathians (Birkenmajer and Worobiec, in press), Krościenko on the Dunajec (Oszast,

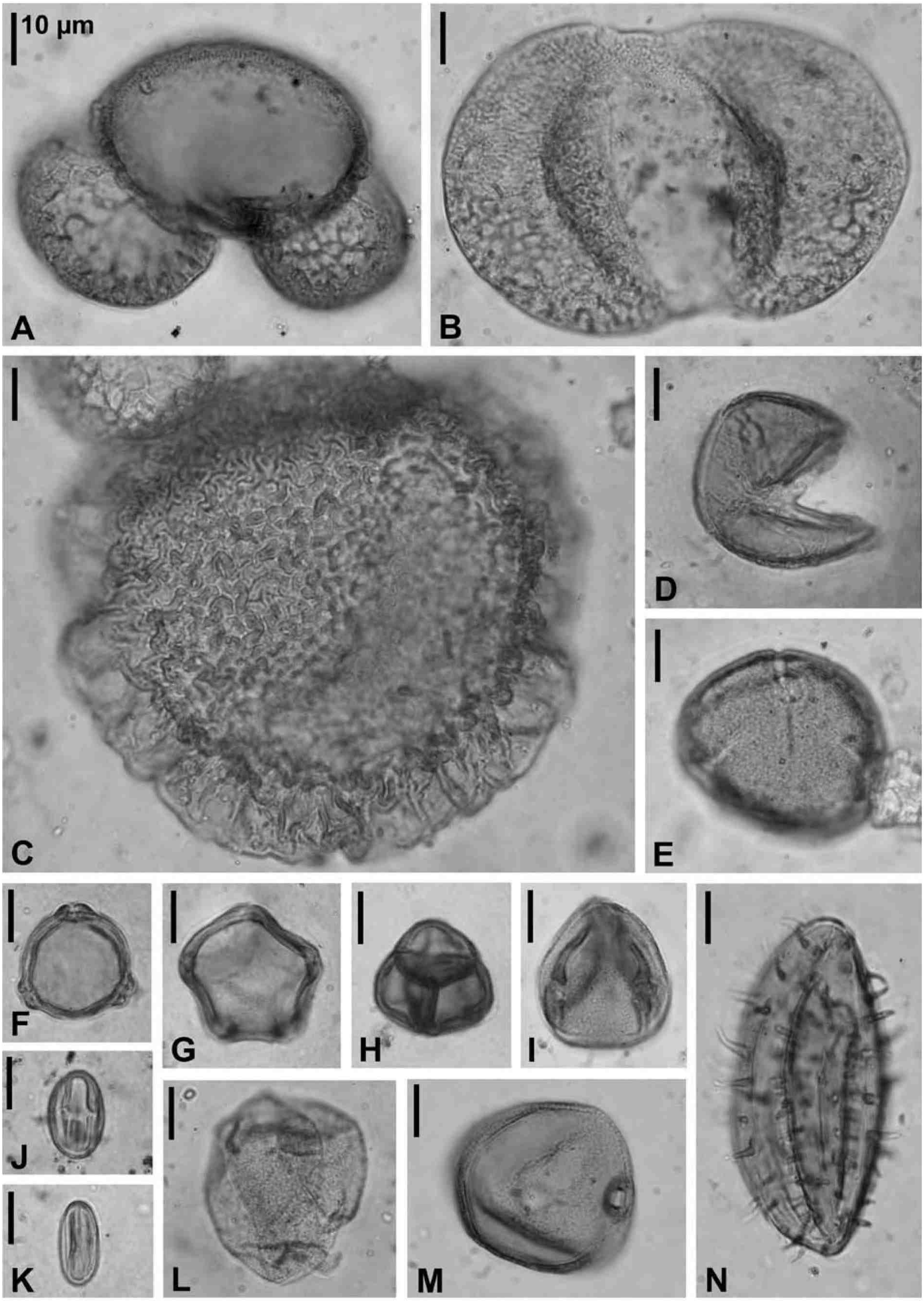


Fig. 8. Pollen grains from Górażdże sinkhole. All scale bars – 10 µm. **A.** *Pinus sylvestris* type. **B.** *Cathaya*. **C.** *Tsuga*. **D.** *Taxodium/ Glyptostrobus*. **E.** *Fagus*. **F.** *Betula*. **G.** *Alnus*. **H.** Ericaceae. **I.** *Nyssa*. **J.** *Castanea/Castanopsis*. **K.** *Tricolporopollenites fallax*. **L.** Cyperaceae. **M.** Poaceae. **N.** *Nuphar*

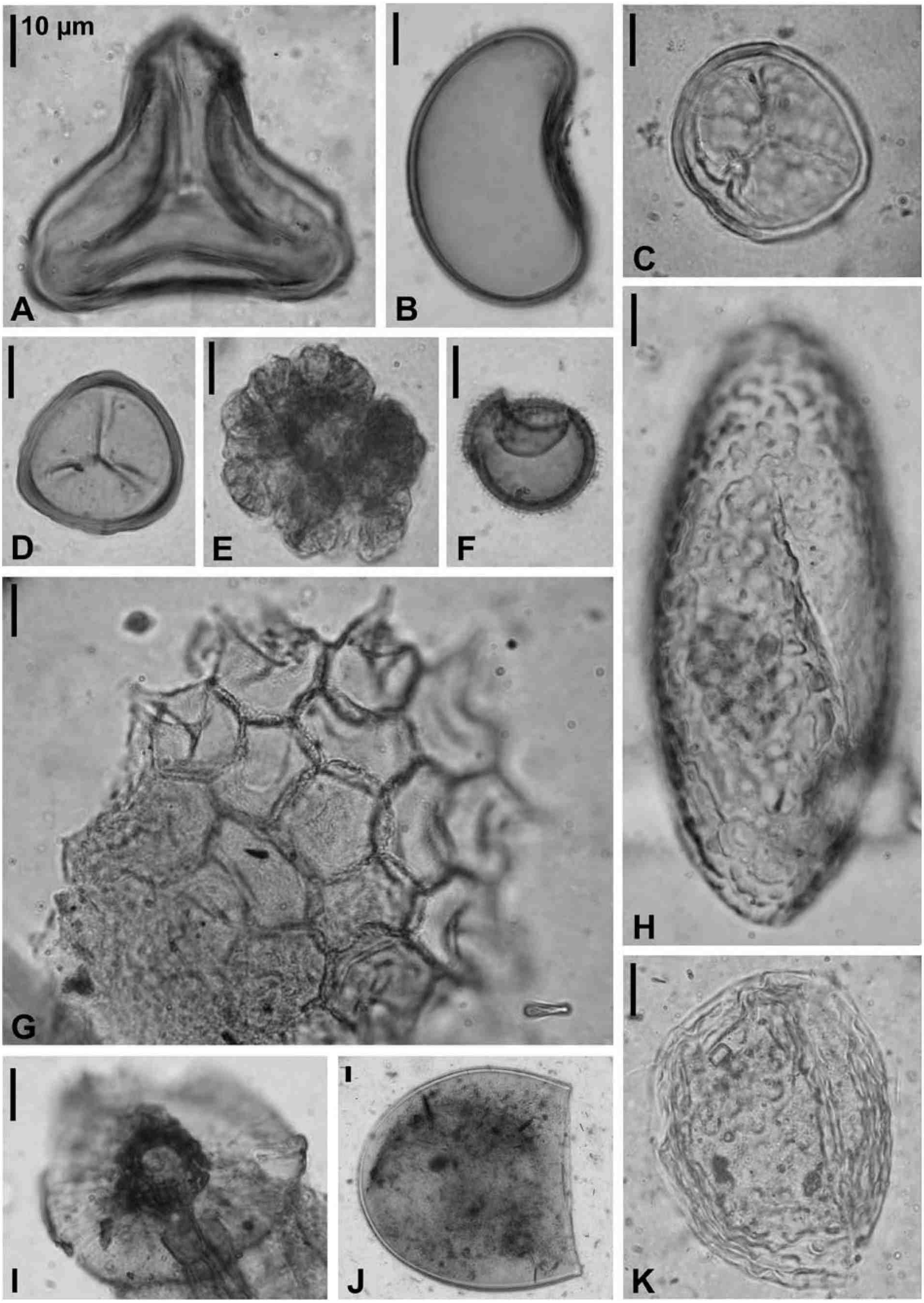


Fig. 9. Spores and non-pollen palynomorphs from Górażdże sinkhole. All scale bars – 10 µm. **A.** *Neogenisporis* sp.. **B.** Polypodiaceae/Davalliaceae. **C.** *Sphagnum* type 1. **D.** *Sphagnum* type 2. **E.** *Botryococcus braunii*. **F.** *Sigmopollis pseudosetarius*. **G.** *Pediastrum* sp.. **H.** *Spirogyra* zygospore. **I.** sporocarp of Microthyriales epiphylous fungus. Non-pollen palynomorphs from sediment covering palaeokarst. **J.** probably Neorhabdocoela oocyte cf. *Strongylostoma radiatum*. **K.** *Zygnema* zygospore

Fig. 10. Location map of Górażdże palaeosinkhole, against some previously palynologicaly studied sites from SW Poland

1973), and Domański Wierch near Czarny Dunajec, Nowy Targ-Orawa Basin, Western Carpathians (Oszast, 1973; Oszast and Stuchlik, 1977). These Pliocene palynofloras (Fig. 10) are dominated by conifers, with a high proportion of *Picea* pollen. Therefore, a Late Miocene age is proposed for the Górażdże palynoflora.

The palynoflora studied is most similar in composition to the spore-pollen spectra of the Late Miocene XI climatic phase – *Betulaepollenites-Cyperaceaepollis* spore-pollen zone *sensu* Ziembińska-Tworzydło (in Piwocki and Ziembińska-Tworzydło, 1995; see also Ziembińska-Tworzydło, 1996, 1998; Piwocki and Ziembińska-Tworzydło, 1997). Deposits, bearing such assemblages, occur within the Poznań Formation, and they were deposited during the Late Pannonian and Early Pontian. Unfortunately, profiles with a well documented XI climatic phase are infrequent in Poland. The assemblages of the XI phase are known e.g. from a thin brown-coal seam in the Orłowo profile (Doktorowicz-Hrebnicka, 1957), as well as from several sections in the Warmia and Mazury region (Słodkowska, 2009). At that time, swamp forests with *Nyssa* and *Taxodium* did not play any important role. They were replaced by moist, riparian forests with *Alnus*. Drier terrains were occupied by mixed forests, with a high ratio of conifers (especially pine) and only with sparse, palaeotropical relics. In the extensive areas of the Polish Lowland and in part of the uplands, only a few shallow basins were overgrown with peat-producing sedge-moss, rush and alderwood communities. They yielded small lenses of lignite, called the 0 (zero) Orłowo seam group (Ważyńska, 1998; Ziembińska-Tworzydło, 1998).

Palynoflora from fluvioglacial deposits

The pollen spectra from the deposits, lying above the palaeokarst, distinctly differ from the spectra of the sinkhole. Their composition is characteristic for Quaternary deposits. The results of pollen analysis also indicates the presence of water bodies, in which e.g. *Sigmopollis*, Zygnemataceae, *Pediastrum*, and *Botryococcus* occurred. In the vicinity, herbs (mainly Cyperaceae, Poaceae and *Sparganium*), as well as mixed and riparian forests, composed of *Pinus*, *Picea*, *Betula*, *Alnus*, and *Ulmus*, *Quercus*, *Corylus*, *Carpinus*, *Fraxinus*, *Salix*, *Tilia* and others, grew. The presence of such taxa as *Quercus*, *Carpinus*, and *Tilia* indicates that the deposit originated during warmer phase(s) of the Quaternary interglacial(s). Unfortunately, sparse palynological data do not permit precise age determinations for these deposits.

ORIGIN OF THE SINKHOLE AND ITS FILL DEPOSITS

The most striking feature of the sinkhole fill is its lack of horizontal stratification. Primary, sedimentary structures (e.g. lamination) are disturbed and the sediments are plastically deformed (Figs 3F, G). Deformations are most intensive within the boundary zone, between the fill and rockhead, where a steep inclination of primary strata is visible (Fig. 3F). The dip of the strata becomes more and more gentle toward the sinkhole centre. Such a succession of deformation and the geometry of the sedimentary fill indicate subsidence of the sinkhole sediments (Fig. 5). The hourglass-shape of the sinkhole indicates that subsidence resulted from the opening of an underlying cavern, with sinking of some of the overlying sediments into the opened cave space. Some angular limestone blocks, found in the sinkhole sedimentary fill, suggest that a collapse event should be also taken into account, as a possible factor in sinkhole development.

The above features and the lithological succession of the sinkhole filling indicate the following sequence of palaeokarst evolution in Tertiary times (Fig. 11). During the first phase, both subterranean and surface forms developed concurrently (Fig. 11A). The surface of limestone rocks underwent decomposition and a pedo-sedimentary complex of terra rossa, 1.5 m. thick, accumulated. With time, the cave system and the overlying surface karst depression became connected and the surface karst deposits – variegated clays, silt sands and limonitic concretions – sank down into the underlying cavern (second phase, Fig. 11B). As a result, an open depression formed. The depression plugged by impermeable, failed clays, gave way to the formation of a small pond (Fig. 11B). The pond gradually was filled with grey clays and lignite sediments. The very fine fraction of clay and lignite deposits, the lack of carbonate component, the lack of fossils (vertebrates), and the blackening (pyritisation) of the chert lithoclasts, indicate that the pond was filled with stagnant, dysoxic and acidic water. Since this part of the sinkhole fill also displays plastic deformations, it may be assumed that the subsidence process continued.

With time and climate changes (cooling?), the depression was filled with white sands and clays (third phase, Fig. 11C), derived most probably from the rewashed and redeposited, Upper Cretaceous sandstones and marlstones (Rogala, 2006; Kazik and Mierzwiński, 2010). The sands are partly cemented by secondary calcite.

From the study of recent sinkholes (Waltham *et al.*, 2005; Ford and Williams, 2007), it is known that the subsi-

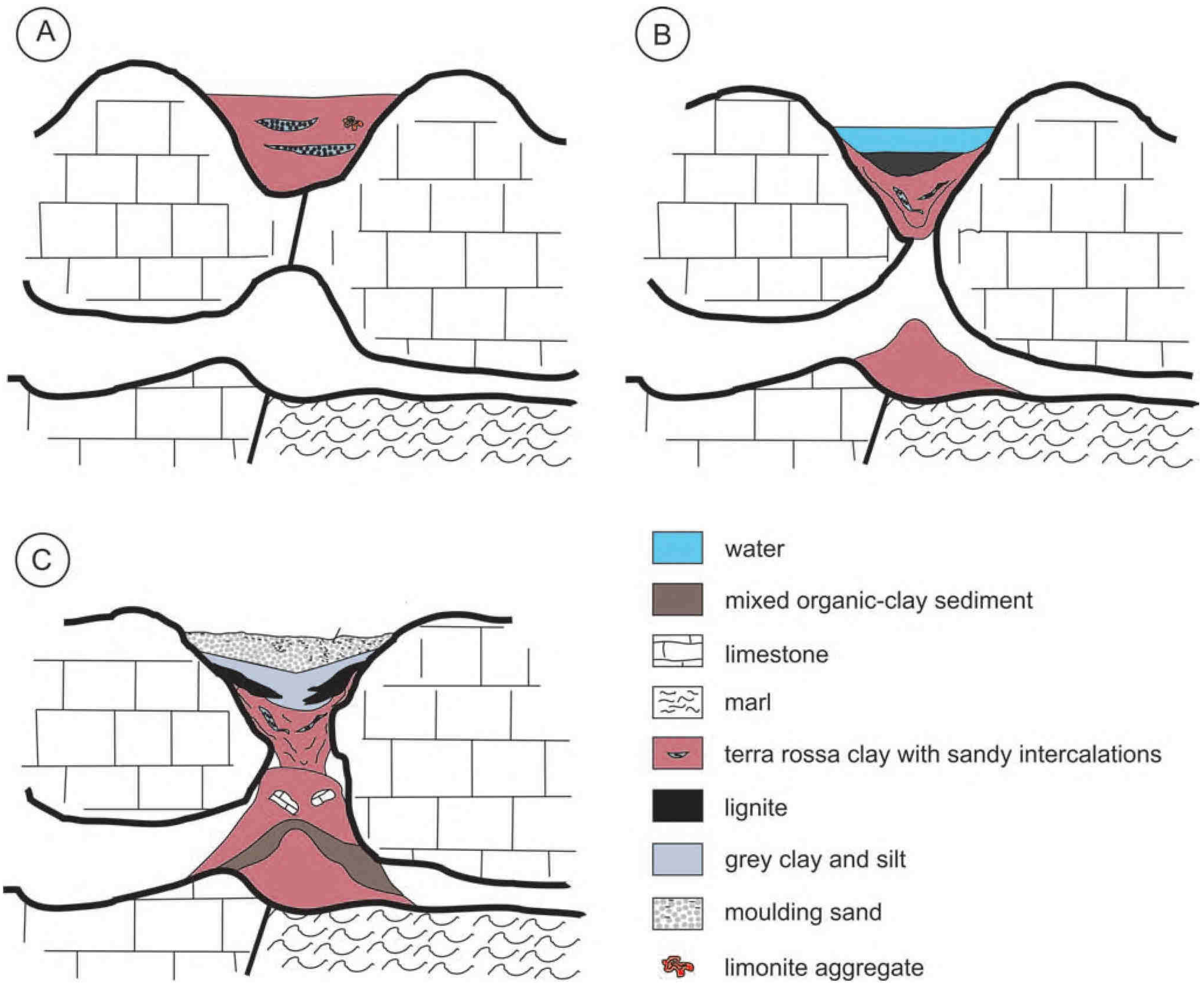


Fig. 11. Model of development of sinkhole studied and its deposits. **A.** First phase. Concurrent processes of cave system formation and subaerial deposition of clayey terra rossa. **B.** Second phase. Opening connection between surface depression and cave. Subsiding of terra rossa soil. Resulting depression gave rise to pond creation and phytoclast deposition. **C.** Third phase. Final collapse and deposition of moulding sands

dence within sinkholes progresses at a gradual rate, reaching several cm a year, but more drastic failure events are quite common. According to synsedimentary deformations (slump and creeping structures, small faults), recognized in the sinkhole fill at Górażdże, it seems reasonable to assume a sporadic mechanism of subsidence; slow sinking was interrupted by occasional events, marked by sudden roof collapse of the underlying cave system.

Since the Tertiary sinkhole system is eroded and covered by fluvioglacial, Pleistocene sands, it is difficult to say what happened between the third phase and the Pleistocene.

With regard to the sinkhole fill composition and in particular the organic component, the absolute lack of diatom opal frustules, a ubiquitous component of Cenozoic freshwater algae assemblages, is very remarkable. The lack of diatom siliceous remnants may be satisfactorily interpreted as being a result of postsedimentary silica dissolution under high pH conditions. The dissolved, diatom-derived silica has been reprecipitated as chalcedony cement and aggregates, commonly found in the lignite deposits (Fig. 4E). This, in turn, evidences fluctuating pH conditions in the sinkhole environment. Chemical conditions ranged from acidic during the first and second phase to alkaline during the third phase. It is very probable that during the latter phase, the alkaline groundwater dissolved delicate diatom frustules. Afterward, pH became again acid or neutral, which led to reprecipitation of silica as chalcedony cement.

CONCLUSIONS

1. The studied karstic sinkhole developed during Miocene time. It represents a subsidence type of karstic sinkhole.

2. Three main stages of sinkhole evolution were recognized. During the first phase, a terra rossa-type soil developed at the surface and a cavern system was formed in the underlying limestones. During the second phase, owing to a

connection between the surface and the cave system and the ensuing subsidence, a water-filled depression formed and a small pond came into being. The depression eventually was filled with moulding sands, derived from rewashed, Cretaceous clastics and marls, as the climate became cooler.

3. The composition of pollen spectra from the palaeosinkhole indicates the presence of mixed mesophytic forests and shows a significant presence of herbaceous and riparian vegetation during the sedimentation of the sinkhole infill. The occurrence of numerous freshwater algae and the pollen of aquatic plants (Nymphaeaceae) evidences the presence of a water body (pond).

4. A characteristic feature of the sporomorph association is an apparent dominance of arctotertiary (including warm-temperate and temperate) as well as cosmopolitan, palaeofloristical elements. Palaeotropical elements are represented mainly by subtropical and palaeotropical/warm-temperate taxa. This indicates a warm-temperate and a mid-wet climate during deposition of the sediments, filling the Górażdże sinkhole.

5. The results of palynological studies of the palaeosinkhole filling indicate its Late Miocene age. Its composition makes it comparable to the *Betulaepollenites-Cyperaceaepollis* spore-pollen zone, typical for the XI climatic phase, distinguished in Late Pannonian and Early Pontian deposits.

6. The results of pollen analysis of samples, taken from deposits lying above the palaeokarst, confirm their Quaternary age.

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